Prompt photons at RHIC

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Abstract

We calculate the inclusive cross section for prompt photon production in heavy-ion collisions at RHIC energies ($\sqrt{s} = 130$ GeV and $\sqrt{s} = 200$ GeV) in the central rapidity region including next-to-leading order, $O(\alpha_{em}\alpha_s^2)$, radiative corrections, initial state nuclear shadowing and parton energy loss effects. We show that there is a significant suppression of the nuclear cross section, up to $\sim 30\%$ at $\sqrt{s} = 200$ GeV, due to shadowing and medium induced parton energy loss effects. We find that the next-to-leading order contributions are large and have a strong p_t dependence.

There is much excitement about the recent long awaited first collisions at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) due to the fact that the energy densities and temperatures created are larger than those ever seen before in a laboratory environment. It is commonly believed that at such high energy density and temperature, a new state of matter, the Quark Gluon Plasma (QGP), will be formed as predicted by QCD. However, the signatures of the Quark Gluon Plasma are non-trivial and hard to interpret. Electromagnetic probes such as dileptons and photons are excellent tools to investigate the Quark Gluon Plasma since once produced, they do not strongly interact with the plasma and therefore carry information about all stages of the heavy ion collisions [1].

Photon production in heavy-ion collisions has been studied extensively [2, 3, 4, 5]. There are several sources of photon production in a heavy-ion collision: thermal photons which are emitted from a thermalized plasma, photons from decays of hadrons such as pions and eta's, and photons produced in early stages of the collision through hard processes. Each of these processes dominates in a specific transverse momentum region. Photon production from hard partonic processes is expected to be the dominant mechanism at high p_t ($p_t > 4$ GeV), while at lower values of p_t ($p_t \sim 3 - 4$ GeV), it is an important background to thermal photons. Here we focus on photon production from hard partonic processes. This is timely as PHENIX collaboration has just collected photon production data up to 6 GeV [6]. Quantitative knowledge of the production cross section of hard photons is also extremely important in deciding whether or not thermal photons can be used as a signal for the formation of the Quark Gluon Plasma at RHIC.

In perturbative QCD the inclusive cross section for prompt photon production in nuclear collisions is given by

$$E\frac{d^3\sigma}{d^3p}(\sqrt{s}, p_T) = \int dx_a \int dx_b \int dz \sum_{i,j}^{partons} F_{i/A}(x_a, Q^2)F_{j/B}(x_b, Q^2)D_{\gamma/k}^A(z, Q_f^2)E_\gamma\frac{d^3\hat{\sigma}_{i+j\rightarrow\gamma+X}}{d^3p_\gamma}$$

where $F_{i/A}(x, Q^2)$'s are the parton distributions in a nucleus, x_a and x_b are the fractional momenta of incoming partons and $D_{\gamma/k}^A(z, Q_f^2)$ are the nuclear fragmentation functions. The parton distributions in nuclei are modified compared to those in hadrons beyond a simple scaling by A. This modification is known as the nuclear shadowing, defined as $S(x, Q^2, A) \equiv \frac{F_i^A(x,Q^2)}{AF_i^N(x,Q^2)}$, and can be parameterized as [7]:

$$S(x, Q^2, A) = \left\{ \begin{array}{ll} \alpha_3 - \alpha_4 x & x_0 < x \leq 0.6 \\ (\alpha_3 - \alpha_4 x_0)\frac{1+k_q\alpha_2(1/x-1/x_0)}{1+k_qA^{\alpha_1}(1/x-1/x_0)} & x \leq x_0 \end{array} \right\} \tag{1}$$

The parameters α_i and k are given in [7]. This parameterization fits all the EMC, NMC and E665 data on nuclear shadowing [8]. All the scales that appear in the cross section, renormalization, factorization and fragmentation, were set to $p_t/2$ as in [9] where it was shown that these choices of scales lead to the best agreement of theoretical predictions with the data. In our calculation we use the MRS99 parameterization of parton distributions in hadrons [10] (also used in [9]) modified by the shadowing ratio as defined in (1). We take A to be 200 throughout this work.

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The double differential parton-parton cross section for prompt photon production, $E\frac{d^3\hat{\sigma}}{d^3p}$, has been calculated to order $O(\alpha_{em}\alpha_s^2)$ in Ref. [9] to which we refer the reader for a complete list of diagrams contributing to next-to-leading order (NLO) and also an extensive discussion of hadronic structure and fragmentation functions. Parton distributions in hadrons [10] and the photon fragmentation function [11] have both been calculated up to NLO, while the nuclear shadowing effect and the photon fragmentation in the nuclear medium have only been obtained in the leading order. We calculate the K-factor, usually introduced as the contribution of the NLO relative to the LO, and show that it is not a constant but rather varies significantly with energy and transverse momentum of the photon. We will define our K-factor relative to the leading order plus the bremsstrahlung contributions since a subset of the bremsstrahlung contributions were included in prior work on prompt photons [4].

In Fig. 1 we show the K factor, defined as $K \equiv \text{NLO}/(\text{Born} + \text{Brems.})$ for prompt photon production in both hadronic and nuclear collisions. The bremsstrahlung contribution in the denominator includes both leading and next-to-leading order bremsstrahlung diagrams.
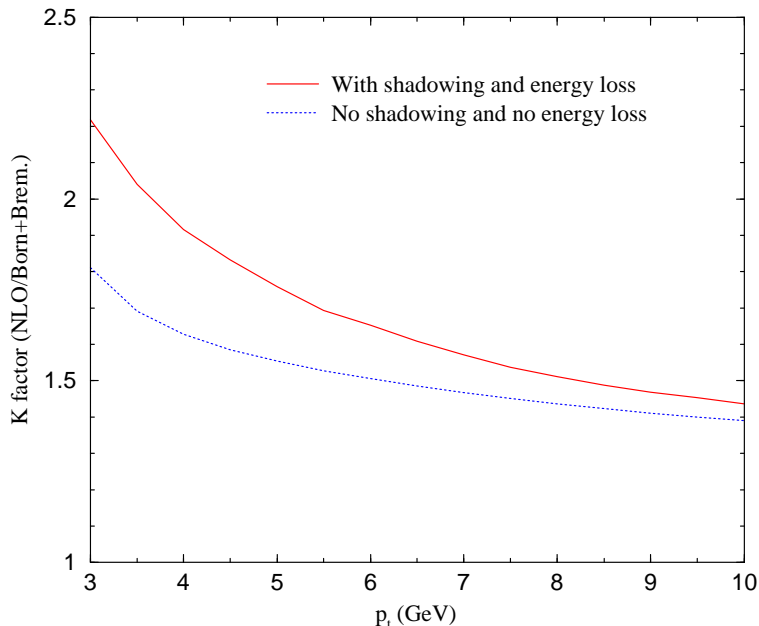

Figure 1: The K-factor for hadronic and nuclear collisions.

We note that K-factor in hadronic collisions varies from 1.4 at $p_t = 10$ GeV to 1.8 at $p_t = 3$ GeV. However, the nuclear K-factor has even stronger p_t dependence, ranging from 1.4 at $p_t = 10$ GeV to 2.2 at $p_t = 3$ GeV. The difference comes from including the nuclear shadowing and parton energy loss in our calculation of the photon production in heavy-ion collisions. We also calculate the standard K-factor, defined as the ratio of the full NLO to the Born cross sections, i.e. $K \equiv \text{NLO}/\text{Born}$. We find this K-factor to be large, ranging from 6 at $p_t = 3$ GeV to 2 at $p_t = 10$ GeV in hadronic collisions and from 5.5 at $p_t = 3$ GeV

to 1.9 at $p_t = 10$ GeV in the nuclear case. Clearly, taking the K-factor to be a constant at all p_t and at all energies is not justified and a full NLO calculation is important.

We also need to consider the nuclear modification of the photon fragmentation functions [11] used in [9] for hadronic collisions. In order to determine the nuclear fragmentation function we follow a simple model of Wang, Huang and Sarcevic [12] and modify the photon fragmentation function, $zD^0(z)$, which gives the probability for a parton to fragment into a photon, to include multiple scatterings of the fragmenting parton from the nuclear medium before it fragments. The nuclear fragmentation function $zD(z)$ is given in terms of the photon fragmentation function $zD^0(z)$ by [12]

$$zD_{A/a}(z, \Delta L, Q^2) = \frac{1}{C_N^a} \sum_{n=0}^{N} P_a(n) \Big[z_n^a D_{h/a}^0(z_n^a, Q^2) + \sum_{j=0}^{n} \bar{z}_a^j D_{h/g}^0(\bar{z}_a^j, Q^2) \Big] \tag{2}$$

where $z_n^a = z/(1 - (\sum_{i=0}^{n} \epsilon_i^a)/E_T)$, $\bar{z}_j^a = zE_T/\epsilon_j^a$ and $P_a(n)$ is the probability that a parton of flavor a traveling a distance ΔL in the nuclear medium will scatter n times. It is given by

$$P_a(n) = \frac{(\Delta L/\lambda_a)^n}{n!} e^{-\Delta L/\lambda_a}, \tag{3}$$

and $C_N^a = \sum_{n=0}^{N} P_a(n)$. For the energy loss per unit distance ϵ_a, we take the energy dependent expression of Baier, Dokshitzer, Mueller, Peigne and Schiff [13], $\epsilon_a = \alpha_s \sqrt{\frac{\mu^2 E}{\lambda_a}}$, where E is the energy of the parton undergoing the multiple scatterings, λ_a is the parton inelastic mean free path and μ^2 represent a screening mass generated by the plasma and serves as an infrared cut off. The first term in Eq. (2) corresponds to the fragmentation of the leading parton a with reduced energy $E_T - \sum_{i=0}^{n} \epsilon_a^i$ after n gluon emissions and the second term comes from the jth emitted gluon having energy ϵ_a^j.

In Fig. 2 we show our results for the invariant photon cross section as a function of photon p_t for RHIC at $\sqrt{s} = 130$ GeV. The effects of nuclear shadowing and energy loss on the nuclear cross sections are shown separately as well as combined. We take $\mu = 1$ GeV and $\lambda_q = \lambda_g = 1 fm$. We find that the nuclear shadowing and the parton energy loss effects result in about 18% suppression of the cross section at $p_t = 3$ GeV and about 4% at $p_t = 10$ GeV.

In Fig. 3 we show the same cross section as in Fig. 2. for RHIC at the higher energy of $\sqrt{s} = 200$ GeV, expected to be reached experimentally sometime this year. As expected, the nuclear effects, shadowing and the parton energy loss become more important at higher energies. At $p_t = 3$ GeV, there is about 30% suppression of the photon cross section while at $p_t = 10$ GeV it is a 7% effect. We expect that this effect can be observed experimentally at RHIC without ambiguity.

In Fig. 4 we show the ratio of hadronic and nuclear cross sections at different RHIC energies of $\sqrt{s} = 130$ GeV and $\sqrt{s} = 200$ GeV. By measuring this ratio one reduces the theoretical as well experimental uncertainties such as scale dependence of cross sections and systematic errors. Clearly, nuclear effects are especially important at lower p_t where the measurements are expected in the near future.
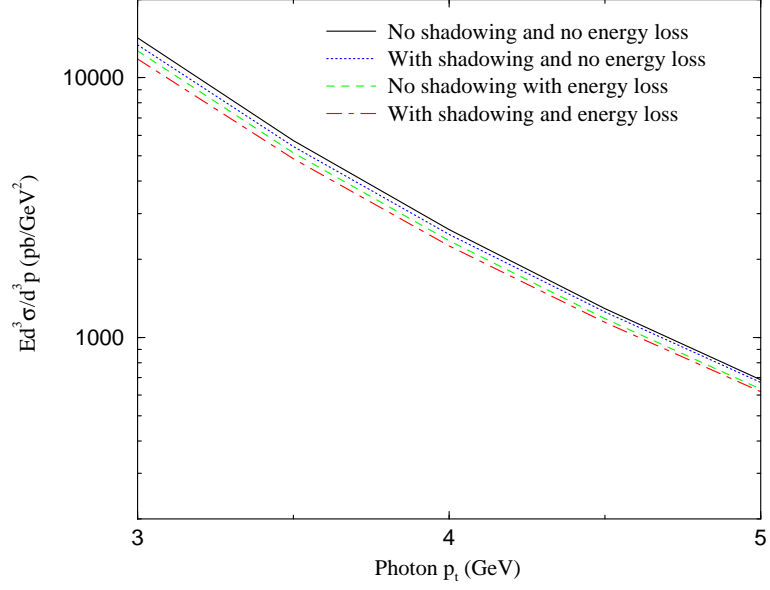
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Figure 2: Prompt photon cross section at central rapidity at $\sqrt{s} = 130$ GeV.
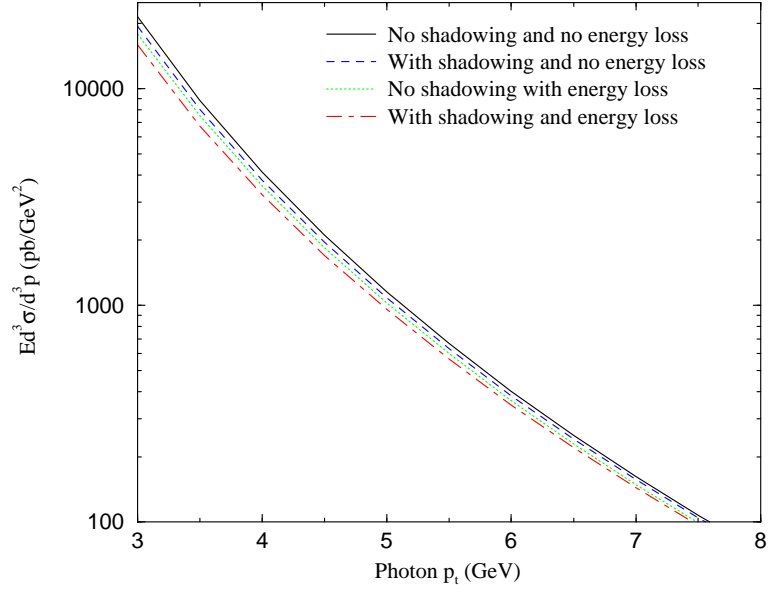

Figure 3: Prompt photon cross section at central rapidity at $\sqrt{s} = 200$ GeV.
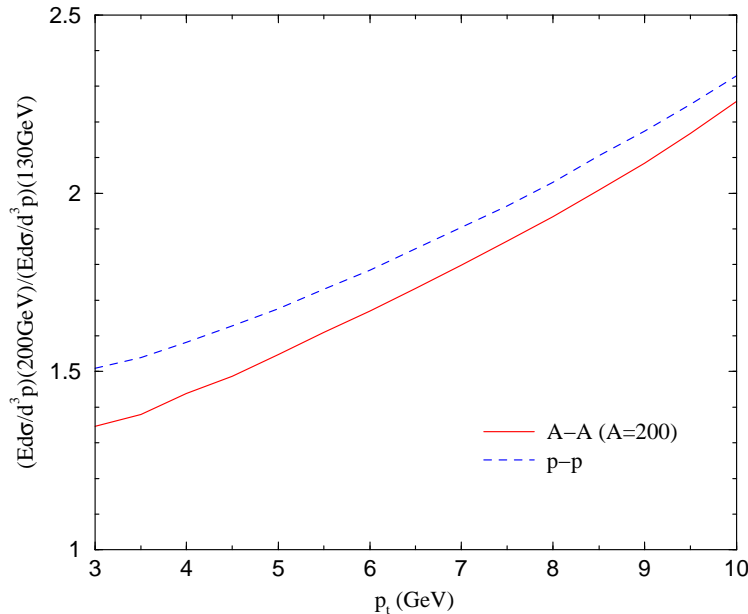
Figure 4: Ratio of hadronic and nuclear cross sections at $\sqrt{s} = 130$ GeV and $\sqrt{s} = 200$ GeV.

The dependence of our results on the choice of energy loss parameters μ^2 and λ_a is shown in Fig. 5 We have varied the values of μ^2 and λ as indicated in the figure. The upper limit corresponds to the case when $\mu = 1$ GeV and $\lambda_q = \lambda_g = 2fm$ while the lower limit corresponds to $\mu = 1$ GeV and $\lambda_q = \lambda_g = 0.5fm$. Variation of these parameters can result in as much uncertainty as 25% for $\sqrt{s} = 200$ GeV at the lowest p_t, but the overall effect is robust.

In summary, we have calculated the prompt photon production cross section for heavy-ion collisions at RHIC including the next-to-leading order corrections, $O(\alpha_{em}\alpha_s^2)$, nuclear shadowing effect and the final state parton energy losses. We have found that higher-order corrections, even relative to leading order plus the bremsstrahlung, are large and depend on p_t of the photon. In case of heavy-ion collisions, the K-factor has even stronger p_t dependence, and thus should not be taken as a constant. Taking K-factor as a constant gives a flatter cross section than the full next-to-leading order calculation. Measurement of prompt photons at high p_t ($p_t > 4$ GeV) should serve as the normalization, as these photons dominate over thermal photons or photons from hadronic decays in this region. However, at lower p_t ($p_t \sim 3 - 4$ GeV) these photons constitute a significant background to thermal photons and photons from hadronic decays. We have also shown that nuclear effects are significant and can be as much as 30% at $\sqrt{s} = 200$ GeV. Therefore, the PHENIX collaboration should be able to, for the first time ever, see the parton energy loss effects due to nuclear media. Extension of our work to p-A collisions at RHIC and heavy-ion collisions at higher energies such as the LHC will be reported elsewhere [14].
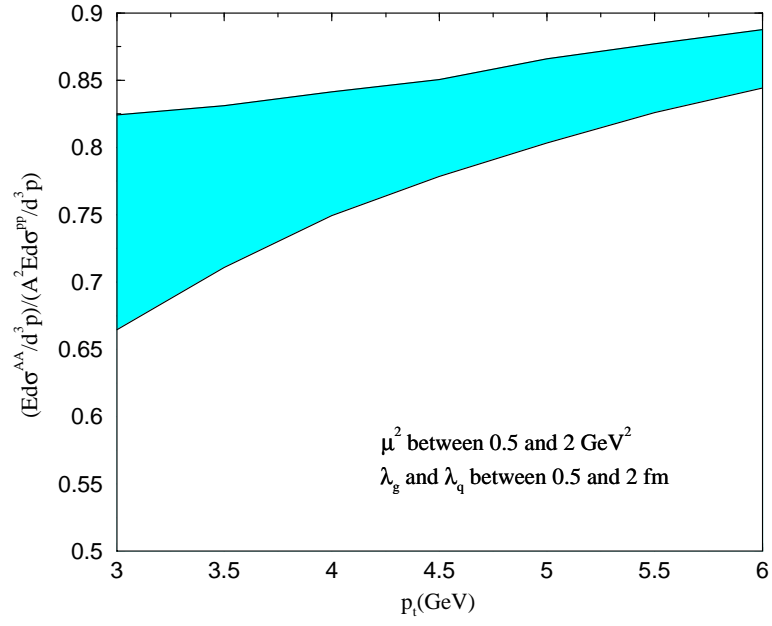
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Figure 5: Uncertainty in the nuclear cross section due to variation of the energy loss parameters at $\sqrt{s} = 200$ GeV.

Calculation of prompt photon cross sections in heavy-ion collisions at LHC energies is especially challenging since one explores the small-x region of phase space where gluons are dominant. Currently there is no experimental data on nuclear structure functions in the small-x region of relevance to LHC. High parton density and higher twist effects such as those discussed in [15] will become important and need to be included. Furthermore, the photon fragmentation functions are also not known at very small values of z which will be explored by LHC. These issues are presently under investigation and results for prompt photons in heavy-ion collisions at LHC energies will be presented elsewhere [14].

Acknowledgments

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